Effectiveness of Grid Systems for Pheromone-Trapping Sparse Gypsy Moth Populations in Mountainous Terrain in the Intermountain West

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EFFECTIVENESS OF GRID SYSTEMS FOR PHEROMONE-TRAPPING SPARSE GYPSY MOTH POPULATIONS IN MOUNTAINOUS TERRAIN IN THE INTERMOUNTAIN WEST

by

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ABSTRACT

Effectiveness of Grid Systems for Pheromone Trapping

Sparse Gypsy Moth Populations in Mountainous

Terrain in the Intermountain West

by

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Two field experiments determined an effective intertrap distance (ITD) for early detection and delimiting sparse gypsy moth (Lepidoptera: Lymantriidae, *Lymantria dispar* L.) populations in mountainous terrain. This study found that current Animal and Plant Health Inspection Service trapping guidelines are not sufficient for early detection of small gypsy moth populations in mountainous terrain. Detection trapping in mountainous terrain should have an ITD of not more than 804 m. Delimiting trapping should use a grid design with an ITD of 152 m.

A related study determined natural adult male mortality in the climate of the Intermountain West, which includes Utah, Nevada, western Wyoming, and southern Idaho. An interaction was found between mortality, temperature, and humidity. During high temperatures, most mortality occurred on the second day. When lower temperatures prevailed, the largest percent mortality occurred on the third or fourth day.

(73 pages)

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LITERATURE REVIEW

Gypsy Moth History and Biology

The gypsy moth (Lepidoptera: Lymantriidae, *Lymantria dispar* L.) is a serious defoliator of hardwood forests, and a major nuisance in urban forests and recreation areas (McManus & McIntyre 1981). *L. dispar* resides in temperate climates of the world, ranging from 20° latitude north in southeastern Asia to 58° north in Scandinavia (Leonard 1974). The gypsy moth is sometimes found in Great Britain, and is considered a major pest in Romania, Japan, and France. It was originally introduced into the United States from Europe in 1869 by Leopold Trouvelot, a French artist and astronomer (Forebush & Fernald 1896). Trouvelot intended to interbreed the gypsy moth with the silkworm moth to develop a race of silkworm resistant to "wilt" disease. During his experiments some eggs were lost and several larvae escaped. The liberated gypsy moth increased so rapidly during the following 10 years that considerable damage was inflicted around Trouvelot's home in Medford, Massachusetts. By 1905 over 5,698 km^2 of woodlands were infested (Gerardi & Grimm 1979).

Congress established the first gypsy moth quarantine in 1913. This quarantine was to prevent the shipment of any insect life stage from infested areas to noninfested areas, and included much of the northeastern United States. Unfortunately, state and federal control measures failed and by 1974 the gypsy moth had increased its range to over 518,000 km^2 (Gerardi & Grimm 1979). In 1981 a record 5.2 million ha were defoliated (McManus et al. 1989). The gypsy moth has been detected in isolated pockets throughout the continental United States. In the western United States, isolated populations of the North American gypsy moth have been detected in Washington, Oregon, Idaho, Utah, Colorado, Arizona, and California (Utah Natural Resources 1989). These remote infestations are thought to be from inadvertent introductions of the insect by the movement of humans.

The gypsy moth is univoltine (having one generation per year) and exhibits complete metamorphosis. This type of metamorphosis contains four distinct life stages: egg, larva (feeding stage), pupa (quiescent transformation stage), and adult (reproductive stage).

L. dispar eggs are deposited in layers, and laid in clusters or masses of fewer than 100 to more than 1,000, but average 400-500 eggs per mass. Oviposition usually begins within 24 hours after mating, and may take several days. Eggs are covered with hair from the abdomen of the female as she oviposits. Hairs are buff colored, and serve to protect the eggs from egg parasites and predators. These hairs may be important in insulating eggs from evaporation and cold winter temperatures (Leonard 1981). Masses vary greatly in size, shape, compactness, and surface area. The majority of egg masses are oval in shape, about 2.5 cm by 3.8 cm, and raised in the center (Gerardi & Grimm 1979). The size of the egg mass is associated with population density and food supply during larval development of the parental population. In low density populations, where food is not a limiting factor, egg masses are larger, on average, than in high density populations (Gerardi & Grimm 1979).

Egg clusters are commonly found within a few feet of the empty female puparium. In forested areas, egg masses are found on tree trunks, in dark sheltered locations such as crevices, and under loose bark and rocks. In urban areas, egg masses are commonly found on or under vehicles, dog houses, and other outdoor objects (Leonard 1981).

Gypsy moth overwinter as diapausing larvae in the egg. Egg embryonation begins soon after ovipositon, and larvae are fully formed in about a month. Development then ceases, in preparation for diapause, and larvae reduce their water content as protection against freezing. They usually spend 8 to 9 months in diapause. In spring, as temperature begins to moderate, larval activity is initiated and water is resorbed. Larvae emerge from egg masses at about budbreak of most hardwood trees (Leonard 1981).

First hatch is correlated with temperature. Most larvae within an egg mass hatch in 3 to 5 days, but hatch between egg masses occurs over a period of 2 to 3 weeks. Hatch may be extended for a month or more if egg masses are laid in cool, shaded areas or at high elevations, such as in mountainous regions (Leonard 1981).

It has been known since the 1890s that windblown, first instars are the main means of gypsy moth dispersal. However, late instars may disperse by crawling short distances. First instars are ideally suited for dispersal, because they weigh less than 1 mg, and are covered with numerous long hollow hairs, which make them buoyant (Gerardi & Grimm 1979). Most dispersal is local, but first instars can be carried for long distances by wind currents. These larvae have been found in wind currents at heights over 610 m (Collins & Baker 1934). Larvae have also been found at a distance of more than 56 km from known, neighboring, infestation boundaries (Collins 1917).

First to third instars usually remain on leaves during the daytime. When larvae reach their third or more commonly fourth instar, they seek sheltered resting sites during the daytime, and feed at night until mature. This shift in diel rhythm is triggered by changing light intensity (Leonard 1981).

Defoliation and Site Characteristics

The gypsy moth is polyphagous and in North America feeds on over 300 shrub, hardwood, and conifer species (Leonard 1981). This large host range, lack of efficient parasites, predators, and inadvertent transportation of various life stages by humans has encouraged the extensive population growth and spread of this pest. Increased vacation travel and interstate commodity shipping have greatly expanded the range of the gypsy moth (Talerico 1981, McManus et al. 1989).

It is well documented that the leaves of some tree species are highly favored by the gypsy moth; some are less preferred, but are eaten regularly when the favored species are sparse. Preference may be variable with age of larvae. Survival of *L. dispar* is determined by the availability of suitable food for early instars. Oak forests in Connecticut and western Massachusetts show that food supply does not typically limit population size in these areas. Only in areas where essentially all adequate food is consumed does the amount of preferred foliage become a limiting factor (Bess et al. 1947).

Quercus sp. (oak), *Populus* sp. (aspen), *Salix* sp. (willow), *Alnus* sp. (alder), and *Acer negundo* L. (boxelder) are highly susceptible to defoliation, and are some of the most favored species of gypsy moth larvae. *Betula* sp. (birch) is susceptible, but some species are favored to a lesser extent. Species classified as intermediate preference include: several *Acer* sp. (maple), *Prunus* sp. (plum and cherry), and several *Pinus* sp. (pine). Some of the least preferred species include: *Fraxinus* sp. (ash) and *Juniperus virginiana* L. (eastern redcedar).

Conifers, for the most part, are not considered favored, but may be subject to defoliation by late instars. However, the Asian strain of *L. dispar* has been introduced to the United States via a ship from Siberia. The Asian gypsy moth has recently been detected in port cities of British Columbia, Oregon, and Washington. Asian gypsy moth has a wider range of suitable host plants than the North American gypsy moth, and presents a substantial threat to American coniferous forests. Rapid spread is expected, because unlike the female North American gypsy moth, which is incapable of flight, the female Asian strain is able to fly for distances up to 30 km (Swadener 1992).

The recent spread of gypsy moth into new and different forest situations created the need to predict susceptibility of forests that have not had previous exposure to this type of defoliator (Houston and Valentine 1977).

Susceptible forests typically grow on dry sites, and are characterized by the following: gravelly or sandy soil, steep rocky ridges, a history of fire, minimal leaf litter, open grazed areas supporting grass and sedges, and stand canopies covering less than 50% of the ground. Open sites are most likely to support pioneer species such as aspen or other species typical of dry exposed sites. Short, scrubby trees (mainly dry-site oaks) have features such as bark flaps, deep bark fissures, and holes or wounds that offer shelter for gypsy moth larvae or pupae (Bess et al. 1947, Houston and Valentine 1977).

Resistant forest stands occur more commonly on rich sites with a reasonably dense crown canopy and well drained deep loam soils where water is not a limiting factor. However, resistant stands may also occur on poor sites that have experienced only minimal disturbance. The composition of these stands may be predominantly oak, as in Connecticut, northeastern and central Massachusetts, and southwestern Maine. Typical resistant stands are composed mostly of *Quercus rubra* L. (red oak), with some *Q. velutina* Lam. (black oak) or *Q. alba* L. (white oak), and very few if any *Q. coccinea* Muenchh. (scarlet oak). Other indicator tree species characteristic of resistant sites are *Acer saccharum* Marsh. (sugar maple), *Fraxinus americana* L. (white ash), *Tilia americana* L. (basswood), and *Liriodendron tulipfera* L. (yellow poplar) (Bess et al. 1947, Houston and Valentine 1977).

Larvae usually pupate in the same resting sites used during their larval development (Leonard 1981). Selection of resting sites may have a significant impact on survival, especially in sparse populations. In mesophytic forests with deep leaf litter, large larvae normally spend the daytime in the litter. Under more xeric conditions they spend the day in trees well above the forest floor. It has been shown that large larvae survive in much greater numbers when they rest, and pupate above the forest floor, rather than in leaf litter (Bess et al. 1947). In Eastford, Connecticut, near the area studied by Bess et al. (1947), Campbell et al. (1977) found that survival during instars four to six was related to larval density. Where 250 larvae per hectare hatched, about 22% survived. Only about 2% survived when larval hatch density was near 100,000. At all densities, larvae that rested or pupated above ground had a larger survival rate than those that rested or pupated in litter. Since only 7.5% of larvae mortality was attributed to disease, it was concluded that most larvae were eaten by density-dependent predators in leaf litter.

Defoliation by the gypsy moth may influence forest succession and stand susceptibility. A stand that is generally resistant, with a considerable proportion of highly preferred host species, can be rendered susceptible by heavy, repeated defoliation that may maintain pioneer species. Susceptibility may also be increased when disturbances open up the stand, and release pioneer species favored by the gypsy moth (Bess et al. 1947, Houston and Valentine 1977).

When a new North American environment is invaded, the initial gypsy moth outbreak seems to be more persistent and to have a greater impact on stands than subsequent outbreaks. This trend may be a consequence of the interaction between *L. dispar* and ensuing dynamic changes in the forest stand. In New England states, defoliation-induced changes in the forest have been similar to those expected from natural succession; however, defoliation seems to have accelerated the process (Campbell and Sloan 1977).

Dead and weakened trees generated by the initial outbreak may provide secure resting locations for large larvae, and pupae. These locations may serve to sustain a massive outbreak over a period of several years (Campbell 1975; cited in Campbell and Sloan 1977). When the initial gypsy moth population declines, selection within species for trees with increased resistance to defoliation, and changes in forest composition that reduce frequency or duration of gypsy moth outbreaks, may result in a semi-stable gypsy moth /forest system (Campbell and Sloan 1977).

A single severe defoliation of a healthy stand of oak is not likely to change the appearance of that stand in following years. However, it will often take ten years for the stand to recover to predefoliation condition. Most mortality will occur in stressed subdominant trees, but repeated defoliation of previously healthy dominant trees may result in considerable tree mortality (Campbell and Sloan 1977).

Additional important factors associated with site susceptibility include aspect, moisture content, length of infestation, and type and severity of forest disturbance (Bess et al. 1947, Crow and Hicks 1990). There is evidence that gypsy moth outbreak conditions are associated with forest disturbance. Disturbance by fire, wind, snow, and human activities such as urbanization, recreational facilities, logging, and maintenance of roads and powerlines often precedes outbreaks. It appears that long-term effects associated with disturbance favor species that are preferred food for the gypsy moth

(Bess et al. 1947).

Utah and Implications for the Intermountain West

The North American gypsy moth was detected 21 July 1988 on the University of Utah campus in Salt Lake City, Utah. A more intensive trapping program was implemented to determine the scope of the problem. High concentrations of male gypsy moths were trapped in the greater Salt Lake City metropolitan area of Salt Lake County. Multiple captures of gypsy moth males induced egg mass surveys. These surveys were performed at 569 locations, ranging from undeveloped areas in the canyons, to high value residential properties (Rivas 1989). Most gypsy moth control programs use 1,236 egg masses per ha as a threshold for treatment. This threshold indicates potential for heavy defoliation the following season (Talerico 1981). Utah egg mass surveys found as many as 2,000 egg masses per 0.4 ha were present in the southeastern metropolitan Salt Lake City area. This area contains Millcreek and Olympus Cove areas, Millcreek Canyon, Big and Little Cottonwood Canyons, and the Holladay area (Rivas 1989). The size of established populations suggested that the gypsy moth had been introduced several years before detection. It appeared that several of the populations in this area were initiated by separate unrelated introductions.

The terrain in the Intermountain West is highly variable, with steeper slopes and higher elevations than typically found in the eastern United States. The Wasatch Mountain Range of northern Utah is part of the middle Rocky Mountain Province. The western edge of this north-/south-running range is situated on a fault zone, causing abrupt, uplifted terrain, and is intersected by steep v-shaped glaciated canyons (Kline 1990).

Gypsy moth populations were found on steep, highly visible, front-face mountain areas. Elevations in these areas range from 1,372 m in the valley foothills to 3,362 m atop Mt. Timpanogos (USDA Gypsy Moth EA 1990).

Utah also hosts several closely related tree species that are favored food of the gypsy moth. These species include: *Quercus gambelii* Nutt. (Gamble oak), *Acer grandidentatum* Nutt. (big tooth maple), *Acer negundo* L. (boxelder), *Acer glabrum* Torr. (Rocky Mountain maple), *Populus tremuloides* Michx. (quaking aspen), *Populus fremontii* Wats. (Fremont poplar), *Populus angustifolia* James (narrowleaf cottonwood), *Betula occidentalis* Hook. (river birch), *Cornus sericea* (dogwood), *Prunus virginiana* L. (western choke cherry), *Alnus incana* (mountain alder), and *Amelanchier alnifolia* (Nutt.) Nutt. (serviceberry) (Kline 1990).

Utah has many coniferous forest communities dominated by *Abies concolor* (Gord. and Glend.) Hildebr. (white fir), *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir), and *Abies lasiocarpa* (Hook.) Nutt. (sub-alpine fir). These communities occur at high elevations on north- and east-facing slopes. Quaking aspen stands, mixed with conifers, occur just below high elevations. Pure aspen stands are usually found at the lower edge of slopes where some runoff water augments natural precipitation.

Oak and maple are the primary mountain brush species and occur at midelevations. These sites have continuous or scattered stands of nearly pure Gamble oak, mixed with big tooth maple and separated by open areas supporting big sagebrush, grasses, and forbs (Kline 1990). Mountain brush communities closely fit the description of gypsy moth-susceptible sites described by Bess et al. (1947).

The mouths of canyons contain delicate riparian cottonwood/water birch communities. These communities occur at elevations of 1,433 m to 2,134 m. Elevations above 2,134 m support mostly water birch and dogwood (USDA Gypsy Moth EA 1990).

Gamble oak and quaking aspen are major components of the Utah landscape, and have clonal root systems with large storage capacities. These reserves give them a significant advantage in recovering from defoliation over non-clonal species. However, constant repeated defoliation reduces their ability to store photosynthate.

Declining overmature quaking aspen, in the absence of disturbance, take about 20 years to become eliminated from the original stand. Severe defoliation of such trees may decrease this interval to as few as 5 to 7 years (Ghent 1958). Mortality in intermediate, co-dominant, and dominant trees is greater with increasing defoliation intensity. Fungal pathogens such as *Hypoxylon, Fomes,* and *Nectria*, as well as insect borer incidence, increase with defoliation intensity (Churchill et al. 1964). Severe defoliation of aspen reduces average leaf size, and increases the tendency toward tip clustering the year following defoliation. Understory fir trees respond to overstory aspen defoliation with increased growth (Duncan and Hodson 1957).

Gambel oak is a deciduous shrub or tree of varying height, up to 21 m, and is sometimes referred to as "Rocky Mountain white oak" or "Utah white oak." It is closely related to white oak typically found in the eastern U.S. (Little 1980).

Gambel oak has shown tolerance to fire. However, intense browsing by goats on Gambel oak creates a 78% net reduction in oak productivity (Riggs and Urness 1989). In this study defoliation was initiated in late spring and was repeated throughout the growing season (Riggs et al. 1988, cited in Riggs and Urness 1989). Clipping studies on Gambel oak do not exhibit a reduction in productivity of this magnitude (Young and Payne 1948, Shepherd 1971, cited in Riggs and Urness 1989). However, clipping studies are generally imposed between mid-summer and early fall. Therefore, reduction in productivity may be attributable to the time of defoliation, and since late spring coincides with the *L. dispar* defoliation period, there is potential for considerable gypsy moth damage in these Utah oak communities.

Utah began a large-scale gypsy moth eradication effort in 1990. During the first year of this program, 8,126 ha were treated by helicopter with the biological insecticide *Bacillus thuringiensis* (Foray 48B; a registered product of Nordisk Bioindustrials, Inc.) (Klein 1990). The successful spray program continued for several years and by 1995 the gypsy moth was considered eradicated in Utah.

Utah has several universities and military bases, which could be continued sources of possible gypsy moth introductions. In addition, Utah currently has a high incidence of relocating individuals, who may inadvertently transport egg masses or other gypsy moth life stages. If *L. dispar* is reintroduced into Utah, and becomes established, it may decrease the quantity or quality of forest and urban hardwood species. Hardwoods such as quaking aspen, big tooth maple, and Gambel oak provide character to the landscape. The addition of color in the autumn is aesthetically pleasing. Defoliation or reduction of these species would be very noticeable to native Utahns. Mortality in forested areas may increase fuel load, thereby increasing the fire hazard.

An indirect ecological effect of defoliation may be negative effects on wildlife habitat. Vital watersheds along the Wasatch Front are covered with Gambel oak and defoliation would have considerable adverse impacts. Watersheds damaged by defoliation may have in increased siltation, loss of shading along streams, resulting in increased water temperatures, and reduced quality from gypsy moth frass and hair.

Tourism is a major industry in Utah. This state contains five National Parks, seven National Monuments, two National Recreation areas, one National Historic Site, and many scenic and water recreation areas. Salt Lake City is a major junction for almost all types of transportation moving through the West. Established infestations in this area could readily be spread by visitors or commercial transport to uninfested areas (Rivas 1989). Increased travel also poses a continuous threat of gypsy moth reintroduction into Utah.

Even though North American gypsy moth populations will likely never reach the levels found in the eastern United States, these are important considerations. Since forests in the intermountain region consist mainly of coniferous species, the possible introduction of the Asian gypsy moth could be an even greater concern.

Pheromone-Trapping of Gypsy Moth

Developmental research into optimal formulation for female gypsy moth attractant began in the early 1900's. In 1970 the pheromone was isolated, categorized as cis-7,8-epoxy-2-methyloctadecane, and designated as "disparlure" (Bierl et al. 1970). Traps baited with a (±) racemate, which contained an equal quantity of both (+) and (-) enantiomers of disparlure, exhibited trap catch many fold less than traps baited with (+) disparlure alone (Cardé et al. 1977*b*, Plimmer et al. 1977, Miller and Roelofs 1978). Pure disparlure, and many of its formulations, attracted more males than did live females (Beroza et al. 1971). However, traps baited with a (±) racemate were not as effective in capturing male moths as were virgin feral females (Mastro et al. 1977).

Yamada et al. (1977) concluded that *cis*(+) disparlure could be the natural sex pheromone of the female gypsy moth. Laboratory and field trials have shown that the (+) enantiomer of disparlure was most efficient in eliciting a strong male behavioral response (Cardé et al. 1977*a*, Cardé and Webster 1979, Yamada et al. 1977, Plimmer et al. 1977, Miller and Roelofs 1978, Elkinton and Childs 1983). The addition of as little as 1% (-) disparlure reduces trap catch significantly, and influences male response, such as reduction in the duration of anemotactic flight, and lowering the propensity of males to fly upwind and land close to the chemical source (Cardé et al. 1977*a*, Miller and Roelofs 1978).

Cardé and Webster (1979) used trap-mark-release-retrap procedures to determine if male behavior was due to differential phenotypic response to either the (-) or (+) enantiomer. They concluded that differential response of males to (+) and (±) disparlure was not due to behavioral phenotypes, and when trap catch is used as a measure of male behavior, (-) disparlure acts in a similar fashion upon all males.

Efforts to develop an economical and efficient trap proceeded concurrently with research to develop the most effective pheromone. During this research several gypsy moth traps were evaluated for efficiency. Of the survey traps tested, the Delta trap (a triangular-shaped trap coated inside with Tanglefoot®) captured a larger percentage of male moths than the Johnson trap (essentially an 8 oz. paper cup with a lid, coated inside with tack-trap® and a hole cut in the top and the bottom) (Mastro et al. 1977).

Live females release pheromone for a limited time, about 4 to 5 days (Beroza et al. 1971). A laminate dispenser, containing 500μg of (+) disparlure (Hercon Environmental Emigsburg, PA), that releases pheromone at a constant rate for several months was developed for use inside traps. Release rates from laminate dispensers are highly correlated with temperature. Release rate increases by a factor of 3.5 for a 10°C (28°C to 38°C) increase in temperature. Release rate for laminate dispensers at 24°C is calculated at 37 ng/h. Laminate dispensers containing 500μg of (+) disparlure remain very attractive until their content drops below 100μg and their release rate below 30 ng/h (Leonhardt et al. 1990). Release rate may drop to approximately 30/ng/h after 16 weeks at temperatures close to 35°C (Leonhardt et al. 1992).

A new type of dispenser was designed as an alternative to the laminate dispenser. This dispenser consists of twisted nylon twine, coated with polyvinyl chloride containing 500μg of (+) disparlure. It is reported to be simple, inexpensive to make, and easier to handle. This new type of dispenser has been shown to be at least as effective as the laminate dispenser (Leonhardt et al. 1993).

The Delta traps with lures containing 500μg of (+) disparlure are currently being used by the USDA to detect and delimit gypsy moth populations in the United States (Thorpe et al. 1993). Traps disseminated before eclosion require little attention during anemotactic flight (Elkinton and Cardé 1981, Schwalbe 1981).

Gypsy moth males orienting to a pheromone source seldom fly directly to it. They usually land near the source, and begin a rapid wing-fanning, walking behavior. They often continue this behavior until the pheromone source is located (Mastro 1981).

Individual male moths do not search around a pheromone source indefinitely (Doane 1968). The mean time of single male searching around live females is 20.52 ± 3.88 s; searching is then terminated. Searching is almost immediately terminated when two searching males touch wings. Males at a single pheromone source usually touch wings at a mean time of 4.38 ± 1.01 s after arrival of the second male (Doane and Cardé 1973).

It has been noted that the male gypsy moth may use visual cues such as tree silhouette for orientation. Males spend most of their searching time in tree-oriented vertical flight, during which they fly up and down the trunk. Tree-oriented vertical flight and walking while wing-fanning in response to pheromone are critical components of male gypsy moth behavior (Cardé et al. 1975, Richerson et al. 1976, Elkinton and Cardé 1983, Elkinton and Childs 1983) and should be considered in trap placement. Previous studies show that male capture is higher at traps next to trees (Granett 1974, Cardé et al. 1977*b*, Elkinton and Childs 1983). The presence of a large tree next to a trap increases air turbulence in the vicinity of the trap. This turbulence causes rapid dispersion of pheromone plumes (Elkinton and Cardé 1983, 1984, Elkinton and Childs 1983). The tree allows male gypsy moths to find the trap more easily, even though the tree may disrupt the pheromone plume of the trap (Elkinton and Childs 1983). Trap catch appears highest at a height of 1 m (or less) from ground level (Stevens and Beroza 1972, Beroza et al. 1973, Cardé et al. 1975).

Detection of new gypsy moth infestations with the use of pheromone-baited traps has been used throughout North America for many years (Ravlin et al. 1987). Methods to determine boundaries in low population densities, such as visual scouting for egg masses, larvae, or pupae, is implausible. The likelihood of finding egg masses in new and small infestations is very remote. Performing egg mass surveys, using any method, over large areas is also costly (Ravlin 1991).

Potential for infestation varies with habitat, host availability, and movement of articles from infested to uninfested areas. High-risk sites include residential areas with a high human turnover rates such as, cities with large universities, or military bases. APHIS recommends trapping in these areas every 2 years, at a density of one trap per

2.6 km^2. Moderate risk sites include contiguous wooded areas accessible to people, large urban areas with limited habitat, and small cities with moderate populations. Trapping for such sites should be done every 2 years, at a density of one trap per 10 km^2. Low-risk sites include noncontiguous wooded areas and rural agricultural regions with widely scattered small towns. Trapping for these low-risk areas should be conducted every 4 years, at a density of one trap per 10 km^2. Special sites include campgrounds, saw mills, state and federal parks, nurseries, mobile home parks, and tourist attractions. Trap density at these sites is recommended every 2 years, using a random set with no more than four traps per site, or 2.6 km^2 (APHIS 1990).

Many males caught in detection traps are assumed to be associated with the movement of vacationers. These catches do not necessarily represent evidence of an established population, so suspect locations are resurveyed the following year with an increased trap density (Schwalbe 1981). Repeat capture provides evidence of infestation in the area.

Delimitation surveys are accomplished using pheromone-baited traps arranged in a grid, covering areas of suspected infestation. This allows the focal point of the population to be determined and defines, or delimits, its range (Schwalbe 1981). Guidelines established by APHIS in 1990 suggested grid density for delimiting surveys to be 16, 25, or 36 traps per 2.6 km^2, with a corresponding intertrap distance of 402 m (1320 feet), 322 m (1056 feet), and 268 m (880 feet). Grids are centered over a 2.6-10 km^2 area, unless evidence indicates that a larger area should be trapped (APHIS 1990).

Information concerning male dispersal is important when determining guidelines for pheromone-baited trap survey and detection programs. The efficacy of any trapping program is based upon the effective zone of a trap, and on male gypsy moth behavior (Mastro 1981). The gypsy moth has a limited dispersal distance, a fact that is beneficial in determining population distribution centers by utilizing capture distribution within the trap grid (Elkinton and Cardé 1980, Schwalbe 1981, Elkinton and Childs 1983).

The probability of male capture is statistically proportional to the distance from the release point (pupal source) and the number released (pupal density) (Granett 1974, Schwalbe 1981). It may also be possible to employ a pupal appraisal as an advanced indication of adult population trends and male mating potential (Granett 1974).

Wing length, when combined with other population density measures, may be used to determine population size. Density-dependent stress and defoliation will conceivably produce populations of smaller adults (Bellinger et al. 1990). A later study by Carter et al. (1991) could not confirm the relationship of male wing length to egg mass density. They did, however, indicate that it may be possible to use mean wing length to determine if male gypsy moths captured in pheromone traps are emigrants from another population that experienced a high level of defoliation. Capture and evaluation of small moths may be beneficial when deciding whether to initiate egg mass sampling at the trap location (Carter et al. 1994).

The level of defoliation in an infested area is largely determined by the density of the larval population (Ganser et al. 1985). Although defoliation can have a significant effect on larval phenology, pupal phenology, and the sex ratio of pupae, the effect on these life stages is not reflected in the capture of male moths in pheromone traps (Carter et al. 1992).

Population information could aid managers in establishing priorities for suppression or eradication programs (Bellinger et al. 1990, Carter et al. 1991). Gage et al. (1990) used trap catch data and defoliation data from 1985-1987 in conjunction with a geographic information system (GIS) to develop a regression model ($R^2 = 0.79$). This model demonstrated that male moth catch could be a good indicator of potential defoliation, and may be used to predict low, medium, and high-risk areas for moth populations the following year.

FIELD EXPERIMENT TO DETERMINE AN EFFECTIVE INTERTRAP DISTANCE TO DETECT AND DELIMIT SPARSE GYPSY MOTH (Lymantriidae: *Lymantria dispar* L.) POPULATIONS IN MOUNTAINOUS TERRAIN

Introduction

Federal, state, and county governments coordinate efforts to control the gypsy moth with systematic detection, delimitation, suppression, and eradication programs. Detection of newly introduced populations and the suppression of new infestations requires an early detection program using pheromone-baited traps.

It is easier and more economical to control, or eradicate, a population if it is detected before becoming established. An uncontrolled population may show a growth rate of 10-fold per generation. For example, if a population starts with 2 adults, then theoretically, by year 7 we could expect 2,000,000 adults in this population (Gerardi and Grimm 1979). Sharov et al. (1995) studied gypsy moth spread along the front of the central Appalachian Mountains in Virginia and West Virginia. They estimated average gypsy moth spread rate during 1989-1992, at 10.7-11.9 km/yr. General spread rate varied considerably from year to year. The maximum rate was 19.4-22.6 km/yr, while minimum rates ranged from 3.8-4.9 km/yr.

To prevent subsequent spread of the gypsy moth, containment techniques are employed around the perimeter of infestations (Holbrook et al. 1960). The primary goals of a gypsy moth trapping program are detection of sparse population centers, monitoring population trends, and estimating population density (Elkinton and Cardé 1981).

The primary reason for conducting a detection survey is to find isolated infestations as soon as possible. Traps placed for detection survey are used in large numbers over a wide geographic area. They should be inexpensive and efficient at low population densities (Schwalbe 1981).

Factors that may influence male moth response to pheromone-baited traps include wind speed and direction, topography, foliage density, predation, temperature, and precipitation (Schwalbe 1981, Carter et al. 1992). The concentration of pheromone near the trap, and the active pheromone plume downwind from the trap, is determined by speed and turbulence of winds and release rate of pheromone (Elkinton and Cardé 1981, 1988).

Pheromone release rate and intertrap distance (ITD) have been shown to affect trap efficacy. The recovery of released insects decreases as intertrap distance increases; hence, the probability of capture is a function of trap density (Schwalbe 1981). Male capture at each trap may also be influenced when intertrap distance is less than the range of attraction. When intertrap distance is reduced to a point where pheromone plumes overlap, the ability of male moths to distinguish the source of attractant is reduced. This phenomenon has been demonstrated for other Lepidoptera, such as the pea moth (*Cydia nigricana* F., Lepidoptera: Olethreutidae) (Wall and Perry 1978, 1980, 1981), and is the basis of mass trapping techniques used in eradication programs (Perry and Wall 1984).

Mass trapping densities vary from 3 to 10 traps per 2.6 km^2 with an intertrap distance of 20-37 m (APHIS 1990).

High capture efficiency of pheromone-baited traps makes release-recapture studies for the gypsy moth feasible. This type of study necessitates use of laboratory-reared moths to insure sterility. A key assumption for such a release technique is that laboratory-reared and feral gypsy moths have similar dispersal and pheromone response characteristics (Elkinton and Cardé 1980). Several studies have shown this assumption to be valid. Waldvogel et al. (1982) found no difference between reared and wild male response to pheromone in a flight tunnel. Mastro (1977) determined that there was no difference in the mating frequency between reared and wild male gypsy moths. Mastro (1978) found no difference between the response of feral and reared adult males to pheromone sources or periodicity of responses. Mastro et al. (1989) found no difference in the periodicity or longevity of mating between reared and wild gypsy moth males (Mastro 1977, 1978, Mastro et al. 1989, cited in Keena and ODell 1994).

In previous research, Schwalbe (1981) released marked male gypsy moths into the center of a grid (Fig. 1) of Delta traps containing 100μg (+)disparlure. His study used an eight-by-eight grid with ITD of 88 m; a six-by-six grid, ITD of 175 m; and a four-by-four grid, ITD of 350 m. Traps withing grids captured 35.4%, 7.9%, and 5.1%, respectively. Within the 350-m grid, 3.5% were recovered at 200 m, 0.62% at 450 m, and 0.38% at 600 m from the release point. In all cases the largest percentage of captured moths was at the traps closest to the release point.

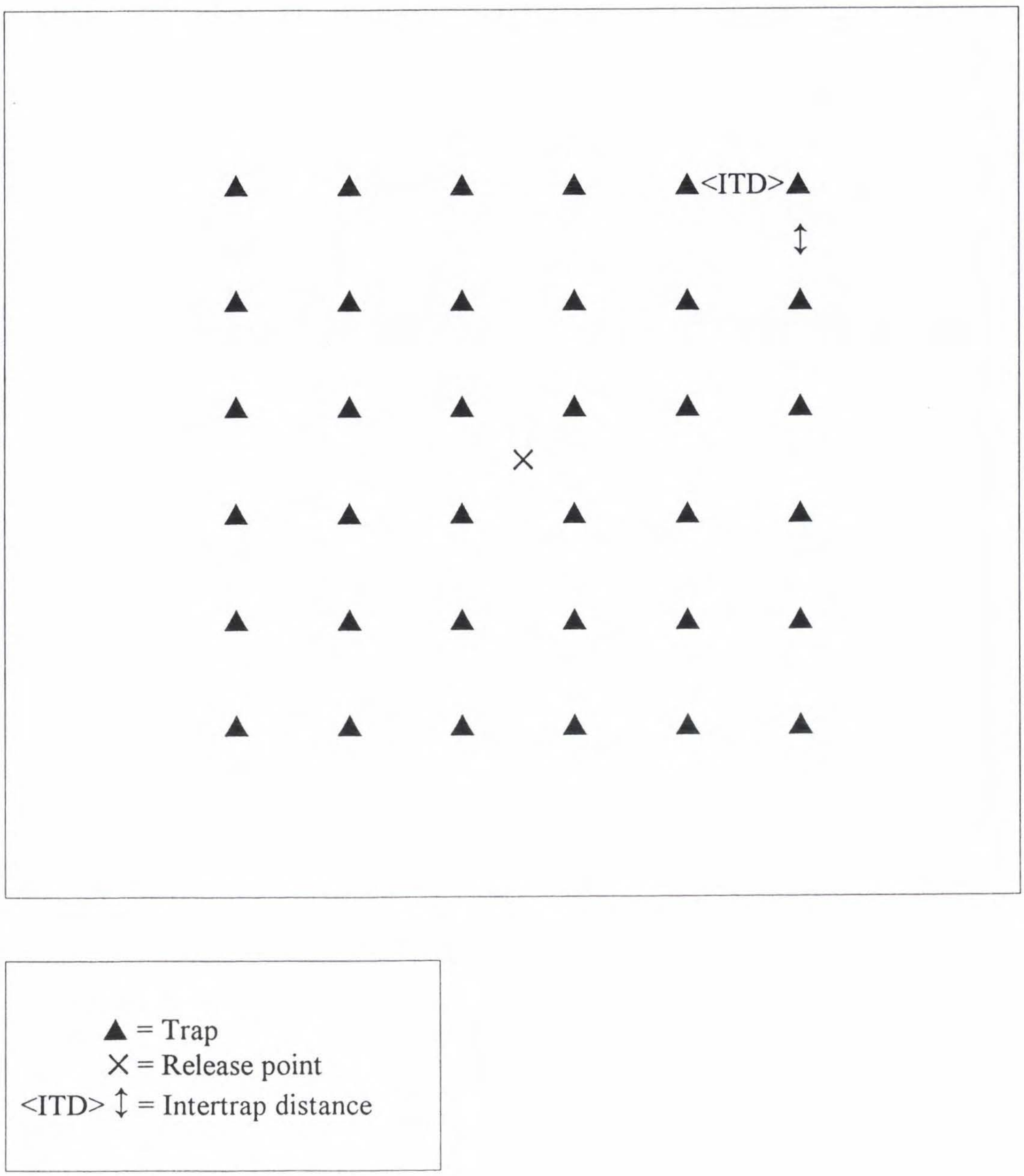

Fig. 1. General six-by-six trapping grid design showing intertrap distance and center release point.

A similar experiment was conducted over a larger area with greater intertrap spacing to simulate detection surveys commonly used in areas with a history of gypsy moth, or in high-risk locations. A 65-km^2 and a smaller 2.3-km^2 forested area were overlaid with a ten-by-ten grid with ITD of 805 m, and a six-by-six grid with ITD of 304 m, respectively. These densities are widely used in Michigan and elsewhere. The 805-m grid captured 0.92%, and the 304-m grid captured 12.7% of the released males (Schwalbe 1981).

Increased wind turbulence along with other factors such as relative humidity and temperature, associated with broken and steep mountainous terrain, could conceivably influence trap efficacy. A study by Start et al. (1975) in Huntington Canyon, Utah, showed that dilution rate of airborne gases in mountainous terrain differ from that found on open flat terrain, under similar stability conditions. Differences vary with changes in Pasquill meteorological stability categories (Pasquill 1961, Turner 1961, cited in Start et al. 1975). Calculations in canyons using parameters derived from flat terrain show that, in neutral stability, dilution within canyon axial concentrations were five-times greater than dilution on flat terrain. During strong inversion, canyon plume centerline dilutions were fifteen-times greater. Enhanced mechanical turbulence associated with wakes from pronounced terrain irregularities, wind-flows near mountain tops, and density flows originating in side canyons are believed to be some of the mechanisms affecting plume effluent dilutions within Huntington Canyon (Start et al. 1975).

Current APHIS trapping guidelines may not be sufficient for survey and eradication situations encountered in Utah's mountainous terrain. Time, effort, and expense allocated to eradication may be significantly reduced if gypsy moth introductions could be detected and delimited within 1 to 2 years. The objective of this project was to identify new or improved detection and delimiting trapping methods appropriate in mountainous terrain. This project consisted of three separate studies. The first study was devised to determine an efficient ITD for delimiting sparse gypsy moth populations in mountainous terrain. The second study was designed to determine the an effective ITD for early detection of these sparse populations. The third study was initiated to determine adult male gypsy moth mortality in the climate of the Intermountain West.

Study I

Delimiting type trapping in Utah was designed with intertrap distances of 152, 304, and 610 m, which are similar to current APHIS guidelines of 268, 322, and 402 m. However, because of the irregular terrain these intertrap distances have been inexactly applied. For safety reasons, instead of using exact coordinates, traps were placed to follow contours. This has resulted in intertrap distances greater than, or less than, the standard 304 m.

The objective of this field study was to determine an effective ITD for delimiting sparse gypsy moth populations in mountainous terrain. It investigated the relationship between ITD and effectiveness of current guidelines when applied to mountainous terrain. This study also related trap catch to factors associated with terrain such as elevation, aspect, slope, temperature, relative humidity, wind speed, and wind direction.

Materials and Methods. Thirty-six Delta traps baited with 500μg (+) disparlure were arranged in six column by six row grids with three intertrap spacing patterns of 152, 304, and 610 meters. Traps were placed at precise grid intersections. Statistically, this can best be described as a split plot design. Each grid spacing pattern was repeated at two locations, giving a total of six grids. Approximately 1,000 sterile 1- to 2-day-old male gypsy moths were released at the center of each grid. Each release was repeated three to four times. This field study was conducted during mid-July through late August of both 1993 and 1994.

Two factors limited the choice for possible release sites. First, sites could not have current gypsy moth populations because if nonreleased moths were captured, it could confound the results. Second, permission was needed from land owners for access to and use of possible sites. As a result, five sites were located in the Oquirrh Mountains, near Tooele, Utah (approximately 56 km southwest of Salt Lake City), and one site was located near Morgan, Utah (approximately 48 km northeast of Salt Lake City).

Each trap within a grid was given a number (written on the exterior of the trap) and was recorded on a topographic map. There were four topographic quadrangles in which sites were located (Fig. 2). The five sites located near Tooele were recorded on three of the four quadrangles. The Tooele quadrangle (112° 22' 30" - 112° 15' / 40° 37'

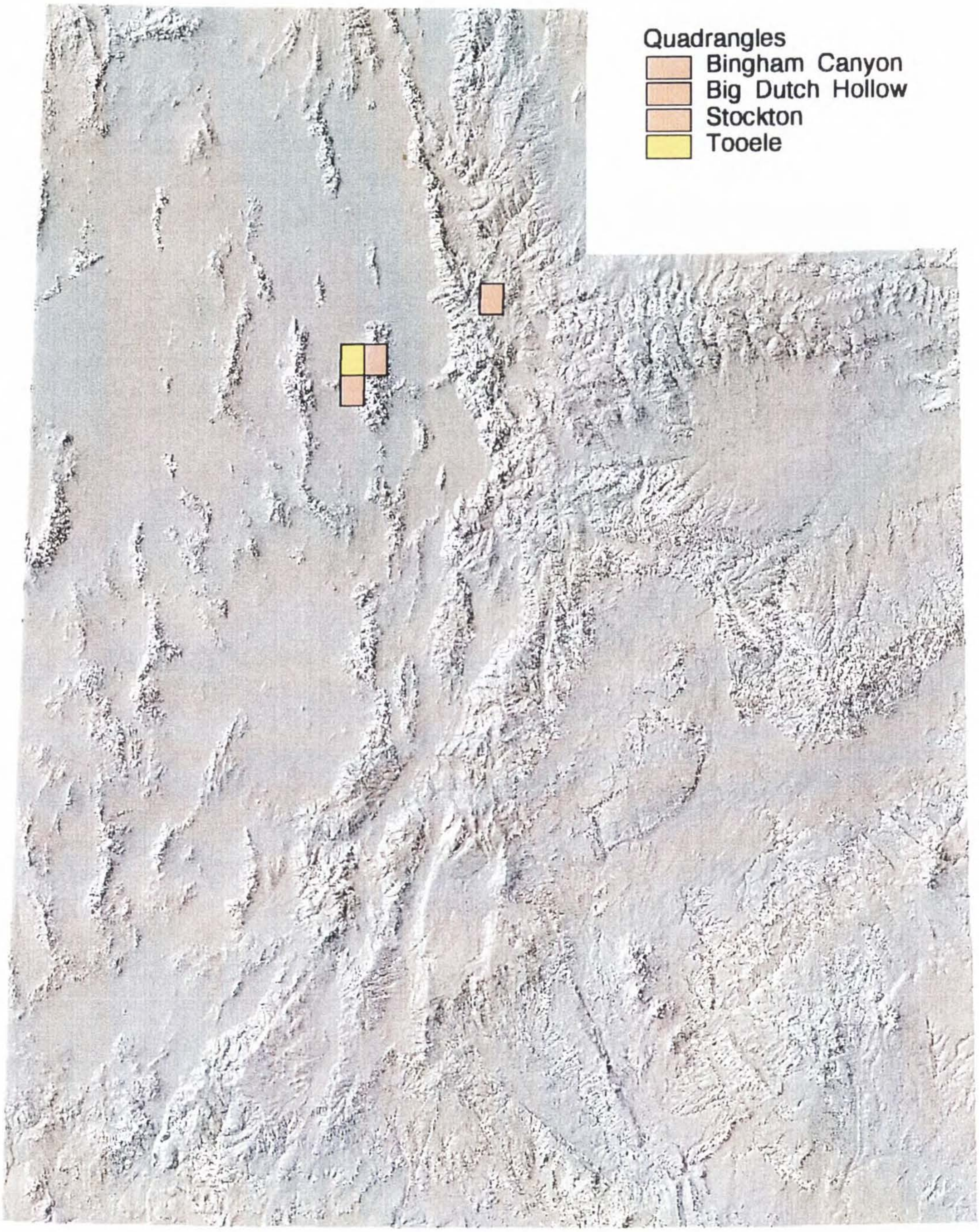

Fig. 2. Geographic information system (GIS) image of Utah, showing the location of quadrangles used in this study.

30" - 40° 30') contained one of the 610-m grids. The Stockton quadrangle (112° 22' 30" - 112° 15' / 40° 30' - 40° 22' 30") is directly south of the Tooele quadrangle and contained one of the 152- and both of the 304-m sites. The Big Dutch Hollow quadrangle (111° 37' 30" - 111° 30' / 40° 52' 30" - 40° 45') is directly east of the Tooele quadrangle, and contained the other 152-m site. The second 610-m site was located near Morgan and was recorded on the Bingham Canyon quadrangle (112° 15' - 112° 07' 30" / 40° 37' - 40° 30'). Fig. 3 is a 30-meter digital elevation map (DEM) of the Stockton quadrangle. This DEM shows one of the 152-m grids and both of the 304-m grids and demonstrates grid placement.

Traps were placed at a height of approximately 1 m above ground level, preferably on tree branches. A weather station was placed near grid center at one location for each intertrap spacing pattern. Weather stations collected temperature, relative humidity, wind direction, speed, and vertical wind. The three remaining sites had weather data recorders, which measured temperature and relative humidity. However, most of these data recorders were faulty and did not collect data accurately. Weather information ultimately used in analysis of these three plots was obtained from the Utah Climate Center at Utah State University. These data were from a weather station in Grantsville, Utah, which is approximately 32 km west of the sites located in Tooele, Utah.

This study used male gypsy moths reared in lab culture at the APHIS Gypsy Moth Methods Development Laboratory, Otis Air Force Base, Massachusetts. Gypsy

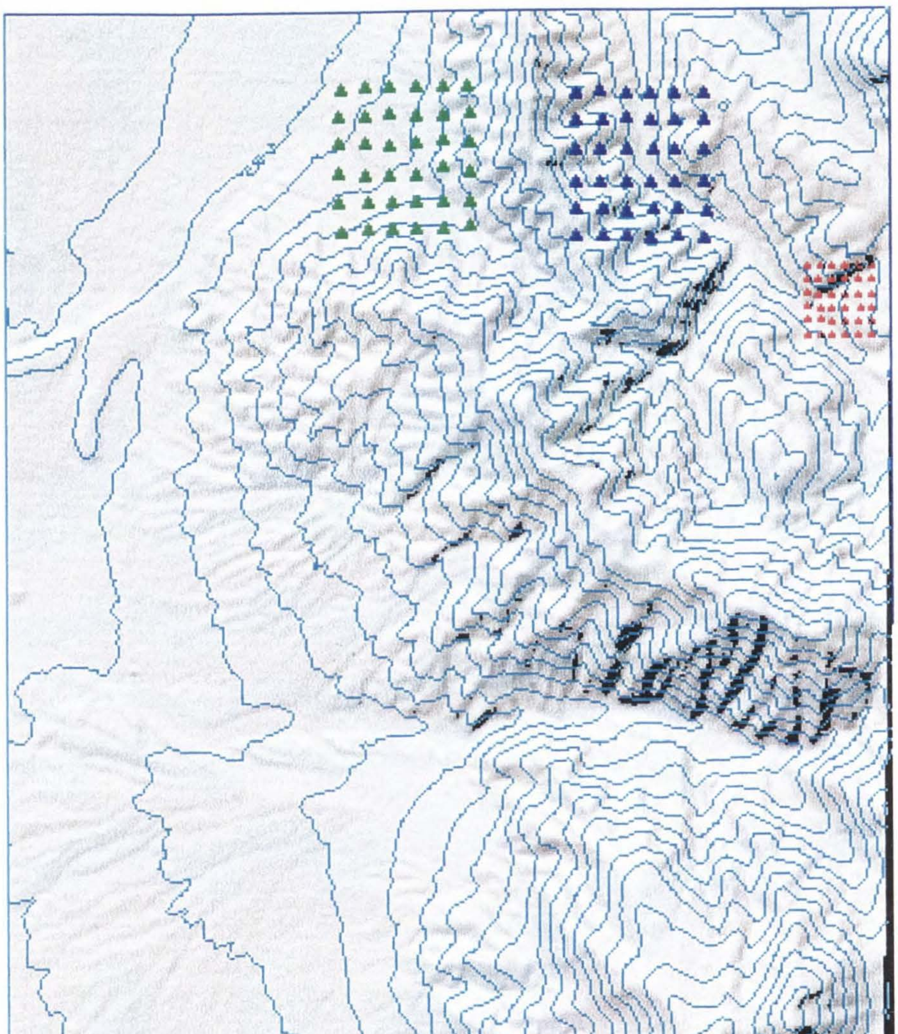

Fig. 3. Thirth-meter digital elevation map (DEM) of the Stockton quadrangle, demonstrating grid placement.

moths were sexed and irradiated at 15 krads to sterilize them. Males, shipped as pupae, arrived in 0.550-liter containers. After pupae were received, they were distributed 50-100/0.551 liter cup, and held in a greenhouse at temperatures between 21°-27°C. After several days it appeared that pupal cases were drying out, making enclosure difficult and creating mortality ≈60%. It was hypothesized that increasing humidity levels could alleviate this problem. Therefore, if humidity dropped below 60%, the greenhouse was sprayed with water to wet the soil floor and flood the air with mist. This procedure maintained a relative humidity between 60%-70%, and pupal mortality was reduced to ≈40%. At night when the greenhouse was unattended, the temperature control was set at 16°-18°C, to reduce adult male moth activity.

Adult male moths were collected from pupal cups using butterfly forceps. They were grasped on the ventral and dorsal surface of the thorax, and transferred to new cups. Transfer was done early in the morning before the greenhouse warmed up. While still cool, moths were inactive, facilitating transfer. Each new cup contained 25 adults. Cups containing adults were placed in a refrigerator at 16°C to prevent damage from fluttering.

When approximately 1,000 1- to 2-day-old adult males were harvested, they were removed from the refrigerator, placed in a cooler, and transferred to the release site. Once at the grid site, moths were removed from the cooler, allowed to warm up, and released from the center of the grid. This procedure was repeated three to four times for each grid site.

Egg masses, provided by the APHIS Gypsy Moth Methods Development Laboratory, Otis Air Force Base, Massachusetts, were used to obtain observed egg hatch data for Utah. These data were gathered every 3 to 4 days in 1991, on six sterile egg masses in each of nine sites, varying in elevation from 1,357 to 2,220 m (Schaub et al. 1995). To determine spray times for the Utah eradication program, the observed egg hatch data were used to initialize GMPHEN, the gypsy moth phenology model (Sheehan 1992). This model predicted that adult eclosion and flight should begin in late July through August. Therefore, release time for this experiment was late July through August 1993 and 1994.

Cardé et al. (1974) reported that the greatest number of males was attracted to pheromone traps from 1100 to 1600 h. Giebultowicz et al. (1992) reported the greatest attraction occurred between 1200 and 1800 h. Therefore, release took place sometime between 0900 and 1400 h, allowing moths to warm up before peak flight. Moths were released by opening the containment cups and launching the moths into the air. This procedure ensured those released were capable of flight. Moths that did not appear able to fly were killed and subtracted from release data.

Previous studies determined that after the second day very few moths are captured (Elkinton and Cardé 1980, 1981). Male activity steadily decreased after the first day, and very few 4-day-old moths respond to any pheromone source (Mastro 1981). To ensure that all responding males had been captured, trapping grids were not checked by Utah gypsy moth trapping crews until 4 to 5 days after release. Traps that captured a moth(s) were removed and replaced. Species of moths in traps were verified. The trap location within the grid and the number of moths per trap were recorded.

Statistical analysis for this study was done using an SAS mixed model ANOVA (SAS Institute Inc., software version 609 for Sun Solaris). Release was done at the 610-m site located in the Tooele quadrangle in 1994, but not in 1993. With incomplete data for this site, it was necessary to drop it from analysis. Many times only three releases per site per year were possible, so analysis was restricted to three releases per site per year.

Results. Preliminary analysis showed no significant difference between sites within the same grid sizes. Consequently, sites within grid sizes were pooled. There were no significant differences between releases. Therefore, analysis assumed that releases were independent replicates. Table 1 shows the results of the SAS mixed model ANOVA tests of fixed effects, all of which show significance ($\propto = 0.05$). Least squares means for trap catch data from 1993 and 1994 are presented in Table 2. The column labeled LSMean (Table 2) shows an approximately 50% reduction in capture for each 152-m increase in intertrap distance (ITD). The percent capture least squares mean in the 152-, 304-, and 610-m grid in 1993 versus 1994 is 1.45, 0.67, and 0.19%; and 0.65, 0.35, and 0.16%, respectively. Even though the total proportion captured in each grid was much lower in 1994, the trend of 50% reduction for each 152-m increase in ITD remained about the same.

The results of the mixed model ANOVA for differences of least squares means

Table 1. SAS mixed model ANOVA test of fixed effects for gypsy moth capture data from 1993 and 1994

Source	NDF	DDF	Type III F	P-Value
G	2	2	24.78	0.0388*
Yr	1	1288	13.69	0.0002*
Yr*G	2	1288	4.81	0.0083*

* Indicates significance at $\propto = 0.05$
G = Grid; Yr = Year; Yr*G = Year by Grid.

Table 2. SAS mixed model ANOVA least squares means for gypsy moth capture data from 1993 and 1994

Source	LSMean	SE	DDF	T	P-Value
G 152m	0.0105	0.0018	2	5.89	0.0277*
G 304m	0.0051	0.0018	2	2.84	0.1048
G 610m	0.0018	0.0020	2	0.90	0.4642
Yr. '93	0.0077	0.0018	1288	4.37	0.0001*
Yr. '94	0.0039	0.0018	1288	2.17	0.0306*
Yr*G '93 152m	0.0145	0.0020	1288	7.42	0.0001*
Yr*G '93 304m	0.0067	0.0019	1288	3.48	0.0005*
Yr*G '93 610m	0.0019	0.0022	1288	0.90	0.3699
Yr*G '94 152m	0.0065	0.0019	1288	3.39	0.0007*
Yr*G '94 304m	0.0035	0.0020	1288	1.77	0.0769
Yr*G '94 610m	0.0016	0.0023	1288	0.67	0.5005

* Indicates significance at $\propto = 0.05$
G = Grid; Yr*G = Year by grid.

are given in Table 3. P-values were adjusted using the Bonferroni method. Analysis showed a significant difference ($\propto = 0.05$) of gypsy moth capture between 1993 and 1994 (T =3.70, df= 1288, adj. P = 0.0002). This difference in capture by year, when grid was compared between years (1993 versus 1994), was demonstrated in the 152-m grid (T = 5.32, df= 1288, adj P = 0.0000). However, the 304 m grid (T = 1.99, df= 1288, adj P = 0.7098) and the 610 m grid (T = 0.17, df= 1288, adj. P = 1.0000) did not show a significant difference ($\propto = 0.05$). Fig. 4 demonstrates the raw percent of male moths captured, it shows an obvious difference between years within the 152-m and the 304-m grids, but the proportions captured were nearly equal within the 610-m grid. When grid size was analyzed within 1993, the 152-m grid differed from the 304-m and the 610-m grids significantly. However, the 304-m grid showed no significant difference from the 610-m grid. In 1994, the 152-, 304-, and 610-m grids did not show a significant difference.

The results of the mixed model ANOVA with topographic covariants are summarized in Table 4. This analysis showed that elevation was significant at ($\propto =$ 0.05). However, slope and aspect are not significant at that level. The solution for fixed effects of the covariance parameter elevation (Est. Val. = -0.00000192, df= 1270, SE = 0.0000591) gave a negative estimate value, which indicated a negative association between elevation and capture proportions, suggesting that on average moth capture may increase with decreasing elevation. This estimate was only slightly negative but became a respectable negative value when multiplied by the elevation. This trend was

Table 3. SAS mixed model ANOVA showing differences of least squares means for trap catch data from 1993 and 1994

Source	Diff. LSM	SE	DDF	T	P-Value	Adj. P-Val
G 152m /G 304m	0.0054	0.0011	2	4.97	0.0382	0.1147
G 304m /G 610m	0.0033	0.0014	2	2.47	0.1326	0.3978
G 152m /G 610m	0.0087	0.0013	2	6.53	0.0227	0.0681
Yr '93 /Yr '94	0.0038	0.0010	1288	3.70	0.0002.	0.0002*
Yr*G '93 152m /Yr*G '94 152m	0.0080	0.0015	1288	5.32	0.0001	0.0000*
Yr*G '93 304m /Yr*G '94 304m	0.0031	0.0016	1288	1.99	0.0473	0.7098
Yr*G '93 610m /Yr*G '94 610m	0.0004	0.0022	1288	0.17	0.8640	1.0000
Yr*G '93 152m /Yr*G '94 304m	0.0109	0.0016	1288	6.78	0.0001	0.0000*
Yr*G '93 152m /Yr*G '94 610m	0.0129	0.0020	1288	6.45	0.0001	0.0000*
Yr*G '93 304m /Yr*G '94 152m	0.0002	0.0014	1288	0.11	0.9120	1.0000
Yr*G '93 304m /Yr*G '94 610m	0.0051	0.0020	1288	2.59	0.0097	0.1450
Yr*G '93 610m /Yr*G '94 152m	-0.0045	0.0018	1288	-2.56	0.0105	0.1582
Yr*G '93 610m /Yr*G '94 304m	-0.0016	0.0019	1288	-0.85	0.3931	1.0000
Yr*G '93 152m /Yr*G '93 304m	0.0078	0.0015	1288	5.21	0.0001	0.0000*
Yr*G '93 152m /Yr*G '93 610m	0.0125	0.0018	1288	6.89	0.0001	0.0000*
Yr*G '93 304m /Yr*G '93 610m	0.0047	0.0018	1288	2.65	0.0081	0.1217
Yr*G '94 152m /Yr*G '94 304m	0.0029	0.0016	1288	1.88	0.0599	0.8988
Yr*G '94 152m /Yr*G '94 610m	0.0049	0.0020	1288	2.51	0.0122	0.1830
Yr*G '94 304m /Yr*G '94 610m	0.0020	0.0020	1288	0.96	0.3348	1.0000

* Significant at the 0.05 level.
G = Grid ; Yr*G = Year by Grid; / = compared with.

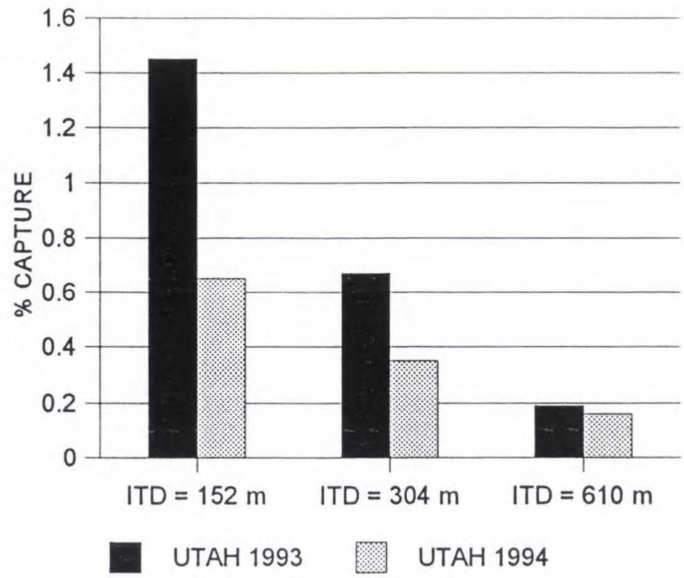

Fig. 4. Percent capture using least squares means of male moths released into grids with different intertrap distances (ITD) for Utah 1993 and 1994.

152- and 304-m grids for both years. The association was more pronounced in the 152-m grid (Est. = -0.00001366, df= 1270, SE = 0.00000843) than in the 304-m grid (Est. = -0.00000033, df= 1270, SE = 0.00000744). There was a significant difference for elevation by year, as well as elevation by year by grid.

The weather variables (average canopy temperature, minimum canopy temperature, maximum canopy temperature, average wind speed, maximum wind speed, average wind direction, and average vertical wind component) were used in an SAS mixed model ANOVA with weather covariants to determine their association with capture proportion. Each covariant factor was analyzed for a relationship with capture proportions. This analysis suggested that trap catch had little association with weather

Table 4. SAS mixed model ANOVA test of fixed effects for gypsy moth capture data from 1993 and 1994, with covariants elevation, aspect, and slope

Source	DDF	Type III F	Pr > F
E	1270	30.55	0.0001*
E*G	1270	10.31	0.0001*
E*Yr	1270	10.29	0.0014*
E*Yr*G	1270	3.86	0.0213*
A	1270	0.03	0.8711
A*G	1270	2.47	0.0850
A*Yr	1270	2.12	0.1453
A*Yr*G	1270	1.32	0.2666
S	1270	0.24	0.6246
S*G	1270	1.67	0.1882
S*Yr	1270	0.34	0.5619
S*Yr*G	1270	0.29	0.7456

* Indicates significance at $\propto = 0.05$
G = Grid; Yr = Year; Yr*G = Year by Grid; E = Elevation; A = Aspect; S = Slope.

variable data used in this study. The only significant ($\propto = 0.05$) relationship to trap catch was in the 152-m grid containing a weather station. In this grid, capture proportions were associated with average canopy temperature (F = 5.19, df= 140, P = 0.0242) and maximum canopy temperature (F = 4.26, df= 140, P = 0.0408). The association was isolated to this grid. These results may be explained by variable topography, vegetative differences, or by chance.

Study II

The intended use of a six-by-six trapping grid system is to delimit or determine the range of possible isolated infestations. A delimiting grid system is used in high-risk areas early detection systems in high-risk areas typically have an ITD of 1,609 m.

Introduction of gypsy moth from an infested area to an uninfested area may occur when outdoor articles are transferred by persons moving into a new residence. The Utah State Drivers License Bureau has provided records of applicants formerly living in an infested area. For several years the Utah gypsy moth eradication program had been trapping at these homes (with owner permission) or in the general area of these individuals. To save time and resources, this program was replaced with a 3,218-m band of traps, set up as lines of traps that are 1,609 m apart with an ITD of 1,609 m. This band of traps was placed along the east bench of the Wasatch Mountain range, from Brigham City to Provo, Utah. This system was designed to detect introduction of gypsy moth in urban areas.

Data collection for 1993 had been completed in the first study and it was obvious that capture in mountainous terrain was considerably lower than in the eastern study by Schwalbe (1981). Therefore, this experiment was designed to determine if a 3,218-m wide band of traps, with an ITD of 804 m, was sufficient for early detection of male gypsy moths originating from recently introduced, isolated, egg masses in mountainous terrain.

Materials and Methods. A 3,218-m wide band of traps with an ITD of 804 m was placed in the urban/wildland interface along the east bench of the Wasatch Mountain range, from Brigham City to Provo, Utah.

It was assumed that from an egg mass containing on average 500 viable eggs, perhaps 100 adult males would survive. Therefore, approximately 100 sterile male moths were released in an area within this band of traps, simulating an egg mass transferred on an outdoor object. Release was repeated three to four times in mid-July through late August, 1994 and 1995. Traps were checked and recorded using similar procedures described in the first field study.

The intent was to repeat this second study method for two consecutive years. Unfortunately, the second year (1995) traps were placed by a different crew and mistakenly placed with an ITD of 1,609 m instead of 804 m. Releases were completed in 1995 before this error was detected. Consequently, results can only be given as a raw number captured and cannot be analyzed statistically from year to year.

Results. All four releases in 1995 within the 1,609-m ITD scheme showed no moth catch. In 1994 within the 804-m ITD scheme, the first release captured one moth in a trap approximately 569 m from the release center. All other releases did not capture any released moths.

It was apparent that to detect introduced gypsy moth within one to two years, in mountainous terrain, the APHIS guideline suggesting an ITD of 1,609 m was not sufficient and an ITD of not more than 804 m would be necessary.

Study III

The western United States, especially the intermountain region, has greater mean summer temperature, greater barometric pressure, and lower relative humidity than is typical of the eastern United States. The intermountain region is extremely xeric compared to the eastern United States. In Salt Lake City, Utah the mean monthly temperature for July and August is 25.3°C and 23.8°C respectively. The mean relative humidity at 1100 h (Mountain time) is 27% and 30%; at 1700 h, 21% and 23%, respectively. In Worcester, Massachusetts, for example, the mean monthly temperature for July and August is 21°C and 20°C, respectively. The mean relative humidity at 1100 h (Mountain time) is 57% and 59%; at 1700 h, 59% and 72%, respectively (Ruffner and Bair 1987). This difference in weather conditions between the Intermountain West and Massachusetts (example of weather conditions in the eastern U.S.) makes it important to determine gypsy moth mortality rates associated with climatic conditions in the western United States.

The objective of the third field study was to associate adult male gypsy moth mortality rate with the climate of the Intermountain West, which includes Utah, Nevada, western Wyoming, and southern Idaho.

Materials and Methods. Three 1.2-by-1.2 m screened cages were used to determine the rate of natural mortality of adult male gypsy moths in the Utah climate. Each cage had a covered lid to provide shade and keep out precipitation. The lid was attached to one side of the cage with a piano hinge, to provide easy access to the cage interior. Weather-stripping attached to all four sides of the lid, in conjunction with chest latches attached to three sides of the box, sealed any possible exit sites for the moths. The front chest latch held a small lock to keep the lid closed to anyone passing by. Cages were designed with adjustable basal legs to level them on the slope, and keep them above the ground. The three cages were placed on the eastern bench above Ogden, Utah, at approximately 3 m apart. This site was in an environment similar to that of the grid release sites in the first study. Cages had varying amounts of shade depending upon differences in vegetation and topography.

A weather pod was placed near the three cages to record temperature and relative humidity. However, the weather data recorders were faulty and information was not recorded accurately, and in some cases data were not recorded at all. Therefore, weather information for this study was obtained through the Utah Climate Center at Utah State University. The weather station used was located in Kaysville, which is about 24 km south of the area where the cages were located.

Fifty adult males were placed inside each cage at 0800 h. Cages were checked twice daily for mortality at 0800 and 1500 h beginning the following day until 100% mortality occurred. Mortality was determined to have occurred when no movement of the moth was observed.

When all fifty males died, a battery-operated vacuum attached to a telescoping broom handle was used to remove them. Fifty fresh moths were placed in the cage the succeeding morning at 0800 h. The first mortality check was done the following morning at 0800 h. This entire procedure was repeated three to five times for each cage.

Analysis for this experiment was done using the SAS mixed model ANOVA. Cage, year, and replication were considered random variables. Since mortality counts were not done at equal intervals, mortality counts at 0800 h were entered as 1 day; counts at 1500 h were entered as 1.3 days. The log of cumulative deaths was used for analysis.

Results. Overall there were no significant differences between years, cages, or year*cage. The overall mean death rate, for 100% mortality, was 4.86 days. Mean death rates in 1994 and 1995 were 4.09 and 5.16 days, respectively. Mean death rates for cages one, two, and three were 4.31, 4.94, and 5.09 days, respectively. This slight difference between death rate by cage may be attributed to the amount of shade supplied for each cage. Cage one was exposed to more direct sunlight than either cage two or three (personal observation). This was reflected in the quicker mean death rate in cage one.

Covariant analysis (Table 5) indicated that maximum temperature and minimum humidity were the most important weather factors. Analysis showed an interaction between maximum temperature and cage ($F = 3.40$, $df = 149$, $P = 0.0360$). This interaction by cage may be attributed to the differing amount of shade between cages. An interaction was seen between minimum humidity and cumulative death rate ($F = 3.98$, df 149, $P = 0.0479$). Minimum humidity by cage was not quite significant at the 0.05 level ($F = 2.77$, $df = 149$, $P = 0.0661$).

Table 5. SAS mixed model ANOVA test of fixed effects for gypsy moth mortality data from 1994 and 1995, with covariants maximum temperature and minimum humidity.

Source	NDF	DDF	Type III F	P-Value
Cage	2	17	3.79	0.0436*
Yr	1	17	0.21	0.6512
Cage*Yr	2	17	0.07	0.9325
MaxTemp	1	149	2.40	0.1232
MaxTemp*Cage	2	149	3.40	0.0360*
MaxTemp*Yr	1	149	0.13	0.7157
MaxTemp*Cage*Yr	2	149	0.06	0.9428
MinHumid	1	149	3.98	0.0479*
MinHumid*Cage	2	149	2.77	0.0661
MinHumid*Yr	1	149	1.11	0.2936
MinHumid*Cage*Yr	2	149	0.17	0.8430

* Indicates significance at $\propto = 0.05$

During high temperatures the largest percent mortality was seen on the third day. When lower temperatures prevailed, mortality rate was considerably reduced, and the largest percent mortality was seen on the fourth or fifth day. Fig. 5 shows more clearly the daily mortality for each repetition and its association to the average maximum daily temperature. If temperatures were greater than 34.2 °C, mortality was generally greater than 90% on the third day. All cages appeared to show a similar trend.

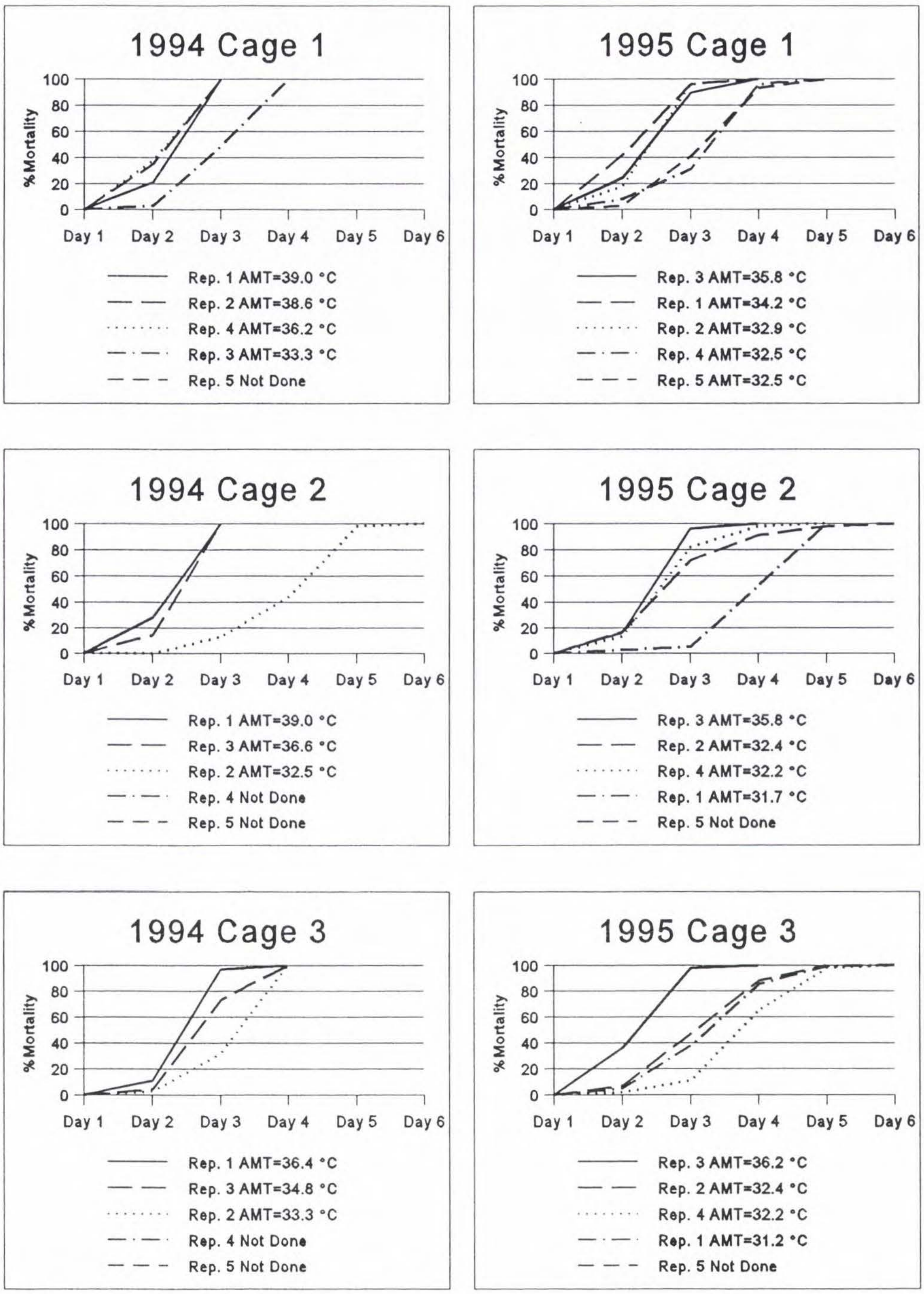

Fig. 5. Graph of each cage in 1994 and 1995, showing gypsy moth mortality in Ogden, Utah; arranged from highest to lowest average maximum temperature for each replication.

Discussion

Trap catch in study I was consistently less than trap catch in similar experiments in the eastern U.S. (Michigan and Massachusetts). It has been shown that the recovery of released insects decreases as ITD increases. However, male gypsy moth capture is much higher in the eastern release study by Schwalbe (1981) than trap catch in this study. In the study by Schwalbe, trapping grids had an ITD of 175, 350, and 805 m and captured 7.9, 5.1, and 0.9%, respectively. The ITD is larger in the study by Schwalbe. However, recovery of released male gypsy moth in Utah 1993 for grids with ITD of 152, 304, and 610 m was 3.1, 1.8, and 0.6%, respectively. This difference is clearly seen in Fig. 6, and may be explained by factors associated with mountainous terrain.

Results of the mixed model ANOVA for Utah capture data indicated a significant difference between years. In general, a higher percentage of moths released into grids was captured in 1993 than 1994. Trap catch in the 152- and 304-m grid was 49% and 28% higher, respectively, in 1993 than in 1994. It appears that capture is reduced by approximately 50% for each 152-m increase in ITD. This trend appears consistent from year to year despite the difference in percent trap catch between years. Least squares means, pooled for both years (Table 2), gives an average capture by grid size, 152, 304, and 610 m, as 1.05, 0.51, and 0.18%, respectively. In 1993, capture was 1.45, 0.67, and 0.19%, and in 1994 was 0.65, 0.35, and 0.16%, respectively. This may be related to the difference in average temperature and relative humidity during July and August 1993

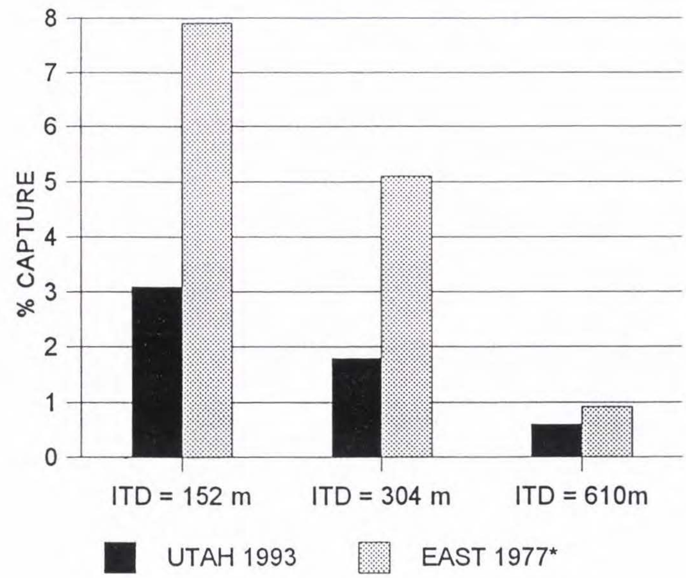

Fig. 6. Percent capture of male moths released into grids with different intertrap distance for Utah in 1993 and similar studies in the eastern United States (Michigan and Massachusetts in 1977) (Schwalbe 1981).

*Intertrap distances for eastern U.S. are approximate; these studies used greater ITDs than Utah, actual ITD 175 m, 350 m, and 805 m.

The raw capture proportion for Utah 1993 was used for comparison; it shows the maximum capture percentages from this study.

(19.6°C, 15% and 20.6°C, 14%), respectively, than in July and August 1994 (24.6°C, 12% and 24.3°C, 12%). Capture will likely vary significantly with temperature. Temperature for 1994 is more indicative of the normal average in Utah for this time of year, suggesting the lower percent capture in 1994 will likely be more representative of the average capture in Utah.

In the mountainous terrain of Utah, the 152-m grid proved to be the most efficient. It was the only grid that had capture great enough to show significance consistently. When pooled over both years (Table 2), the 152-m grid is the only grid showing trap catch significantly above zero ($T = 5.89$, $df = 2$, $P = 0.0277$). The 152-m grid is the only one that may effectively delimit a small population on a consistent basis. The 304- and 610-m grids may delimit a population if it is large enough. The size of that population is unknown at this point, but it will likely be larger than the ≈1,000 male moths used in this study.

It appeared that releases within all grid sizes showed better capture proportions within and down canyon from the release point (personal observation). This trend may be explained by the negative association shown between capture and elevation. This association indicated that a higher capture proportion would be seen at lower elevation. The association shown between capture and elevation suggests that more successful capture may be obtained within canyon bottoms. However, this result may be coincidental, because release for most of the grid sites occurred within a canyon or at the top of a ridge adjacent to a canyon. The path taken to grid centers was from the bottom of the canyon toward the center of the grid. It is possible that since gypsy moth pheromone had been handled at some point, that a pheromone trail was left on the way in and out of the grid. After release, moths may have followed that trail toward the canyon bottom.

It has been shown that insects fly more or less directly upwind toward a pheromone source. Therefore, an association between trap catch and wind direction or wind speed was expected. Increased wind turbulence associated with steep and broken terrain may explain the lack of association between capture and wind direction and speed in this study. The variability in topography may consequently explain the lower overall trap catch seen in Utah. However, wind direction data used in analysis were averaged over a 24-h period. Upon further consideration, if wind direction data could be averaged during peak flight (1100 to 1800 h) when up-canyon winds prevail, analysis may or may not show an association between wind direction and male moth capture.

The association between maximum canopy temperature and average canopy temperature in the 152-m grid may be explained by chance or the variability associated with topography or vegetation. It may also be possible that this association was seen in the 152-m grid because it was the only ITD that had capture great enough to show significance through analysis. More study into this association may prove interesting.

In the second field study for early detection trapping, all four releases within the 1,609-m ITD scheme, suggested by APHIS, showed no moth catch. Within an 804-m ITD scheme, the first release captured one moth approximately 569 m from the release site. All other releases showed zero capture. It was apparent that to detect introduced gypsy moth, within 1 to 2 years, current APHIS guidelines for pheromone detection trapping of gypsy moth were not sufficient in mountainous terrain. An effective ITD for early detection of gypsy moth in mountainous terrain would have an ITD of not more than 804 m. However, an ITD of 804 m was not extremely efficient and using an ITD of 402 m is worth consideration.

In the third field study, covariant analysis indicated that maximum temperature and minimum humidity were the most important weather factors associated with adult male gypsy moth mortality. An interaction was seen between minimum humidity and cumulative death rate. Analysis showed an interaction between maximum temperature and cage. This interaction by cage may be attributed to the differing amount of shade between cages. During high temperatures the largest percent mortality was seen on the third day. When lower temperatures prevailed, mortality rate was considerably reduced, and the largest percent mortality was seen on the fourth or fifth day.

Early detection provides land managers with more options for management of newly infested areas. The results of this project may provide forest and urban land managers with a more efficient methodology for trapping sparse gypsy moth populations in mountainous terrain.

SUMMARY

The primary goals of a gypsy moth trapping program are detection of sparse population centers, monitoring population trends, and estimating population density (Elkinton and Cardé 1981). The primary reason for conducting a detection survey is to find isolated infestations as soon as possible. To detect newly introduced populations and to prevent new infestations from building to damaging levels require an early detection program using pheromone-baited traps.

Factors that may influence male moth response to pheromone-baited traps include wind speed and direction, topography, foliage density, predation, temperature, and precipitation (Schwalbe 1981, Carter et al. 1992). Pheromone release rate and intertrap distance have been shown to affect trap efficacy. The concentration of pheromone near the trap and the active pheromone plume downwind from the trap are determined by speed and turbulence of winds and release rate of pheromone (Elkinton and Cardé 1981, 1988).

Increased wind turbulence, along with other factors such as relative humidity and temperature associated with broken and steep mountainous terrain, could conceivably influence trap efficacy. Therefore, current APHIS detection trapping guidelines may not be sufficient for early detection survey or delimiting sparse gypsy moth populations in mountainous terrain.

Time, effort, and expense allocated to eradication may be significantly reduced if gypsy moth introductions could be detected within 1 to 2 years. The objective of this

project was to identify new or improved detection and delimiting trapping methods appropriate in mountainous terrain. This project consisted of three separate studies. The first study was devised to determine an efficient intertrap distance (ITD) for delimiting sparse gypsy moth populations in mountainous terrain. The second study was designed to determine an effective ITD for early detection of sparse populations. The third study was initiated to determine adult male gypsy moth mortality in the climate of the Intermountain West.

To ascertain an effective ITD for delimiting sparse gypsy moth populations in mountainous terrain, 36 Delta traps baited with 500μg (+)disparlure were arranged in six-by-six column grids with three intertrap spacing patterns of 152, 304, and 610 m. Each grid spacing pattern was repeated at two locations, giving a total of six grid locations. A weather station was placed near grid center at one location for each intertrap spacing pattern. Approximately 1,000 sterile 1- to 2-day-old male gypsy moths were released at the center of each grid. Each release was repeated three to four times. This field study was conducted during mid-July through late August of 1993 and 1994.

Analysis showed no significant difference between sites within the same grid sizes and no significant difference between releases. The least squares means percent capture in the 152-, 304-, and 610-m grid in 1993 versus 1994 is 1.45, 0.67, and 0.19%, and 0.65, 0.35, and 0.16%, respectively. There appeared to be approximately a 50% reduction in capture for each 152-m increase in ITD. Even though the total proportion captured in each grid was much lower in 1994, the trend remained about the same.

Trap catch in this field experiment was consistently less than trap catch in similar experiments in the eastern U.S. (Michigan and Massachusetts). In a study by Schwalbe in 1981, trapping grids had an ITD of 175, 350, and 805 m and captured 7.9, 5.1, and 0.9%, respectively. However, recovery of released male gypsy moth in Utah 1993 for grids with ITDs of 152, 304, and 610 m was 3.1, 1.8, and 0.6%, respectively.

The association of capture to elevation was significant at ($\propto = 0.05$). However, slope and aspect were not significant at that level. On average moth catch may increase with decreasing elevation. This association was seen in both the 152- and 304-m grids for both years.

Trap catch had little association with weather variable data used in analysis for this study. The only significant ($\propto = 0.05$) relationship was in the 152-m grid containing a weather station. In this grid, capture proportion was associated with average canopy temperature and maximum canopy temperature. The association was isolated to this grid. This result may be explained by variable topography, vegetative differences, or by chance.

Preliminary results from the first study indicated that the capture proportions in mountainous terrain were considerably lower than similar studies conducted in the eastern United States. Therefore, the second study was designed to test Animal and Plant Health Inspection Service (APHIS) guidelines for an early detection survey in mountainous terrain. APHIS suggested using an ITD of 1,609 m. This study used a 3,218-m wide band of traps, with an ITD of 804 m to determine if this ITD was sufficient for early detection of male gypsy moths from recently introduced, isolated, egg masses in mountainous terrain. This band of traps was placed in the urban/wildland interface along the east bench of the Wasatch Mountain range, from Brigham City to Provo, Utah.

One hundred male moths were released within this band of traps on four separate occasions during late July and August of 1994 and 1995. In 1995, this band of traps had an ITD of 1,609 m. In 1994, the ITD was 804 m.

All four releases within the 1,609-m ITD scheme, suggested by APHIS, showed no moth catch. Within an 804-m ITD scheme, the first release captured one moth in a trap close to the release center, approximately 569 m from the release site. All other releases did not capture any of the released moths. It appeared that to detect introduced gypsy moth, within 1 to 2 years, current APHIS guidelines for pheromone detection trapping of gypsy moth were not sufficient in mountainous terrain. An effective ITD for early detection of gypsy moth in mountainous terrain would have an ITD of not more than 804 m. However, an ITD of 804 m is not highly efficient and using an ITD of 402 m is worth consideration.

Delimiting an area following a positive capture, within the early detection grid, should be done using an ITD of 152 m. This was the only ITD to have capture great enough to show significance through analysis for the duration of the study.

The western United States, especially the intermountain region (Utah, Nevada, western Wyoming, and southern Idaho), has greater summer mean temperature, greater barometric pressure, and lower relative humidity than is typical of the eastern United States. This region is exceedingly xeric compared to the eastern United States. For this reason it was important to determine gypsy moth mortality rates associated with climatic conditions in the Intermountain West.

Three 1.2-by-1.2 m screened cages were used to determine the rate of natural mortality of adult gypsy moth males in the Utah climate of the Intermountain West. The three cages were placed approximately 3 m apart, in an environment similar to that of the grid release sites in the first study. Cages had varying amounts of shade from vegetation and topography.

Fifty adult males were placed inside each cage and were checked twice daily for mortality until 100% mortality occurred. Mortality was determined to have occurred when no movement of the moth was observed. When 100% mortality occurred, the dead moths were removed. Fifty fresh moths were placed in the cage the following morning. This entire procedure was repeated three to five times for each cage.

Weather information for this study was obtained through the Utah Climate Center at Utah State University. Covariant analysis indicated that maximum temperature and minimum humidity were the most important weather factors. An interaction was seen between minimum humidity and cumulative death rate. Analysis showed an interaction between maximum temperature and cage. This interaction by cage may be attributed to the differing amount of shade between cages. During high temperatures the largest percent mortality was seen on the second day. When lower temperatures prevailed, mortality rate was considerably reduced, and the largest percent mortality was seen on the third or fourth day.

Forest and urban land managers faced with the prospect of gypsy moth introductions in mountainous terrain may find the results of this project useful in planing a methodology for early detection. Early detection provides land managers with more options for management of newly infested areas. Delimiting the range of small populations early provides the option for mass trapping (ITD 37-20 m) or for ground applications of biological or chemical pesticides within the infested area. Adult male gypsy moth mortality was associated with high temperature and low humidity. This information may provide a guideline for the duration of male flight and midseason evaluation of survey traps.

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